

RECONSTRUCTING SUSY THEORIES AT HIGH SCALES

LHC/LC SUSY*X WG

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1. INTRODUCTION

2. SUSY PRECISION ANALYSES AT ELW SCALE

- theor. tools / exp. simulations for LHC and LC
- coherent LHC+LC analyses

3. EXTRAPOLATION TO GUT/PLANCK SCALE

- minimal SUGRA: couplings and mass parameters
- intermediate scales: LR extension
- determining superstring effective parameters

4. CONCLUSIONS

1. INTRODUCTION

SUPERSYMMETRY: stable bridge [q.fluctuations] in extrapolation

electroweak scale → GUT/Planck scale

↑ fundam. [part.] physics region
↑ connection ∼ gravity

- exploration :
- a) proton decay etc
 - b) neutrino physics [if seesaw]
 - c) cosmology [n_B etc]
 - d) high-precision experiments at high energies

⇐ information from all methods limited and partly indirect:
exploit whatever information available, to refine picture

1. SUSY PRECISION ANALYSIS AT ELW SCALE

Program : EX : comprehensive and high-precision SUSY picture at lab scale
in measured observables at LHC/LC/LHC+LC
→ per-mille level

TH : ★ matching precision with experiments when relating
exp observables to basic Lagrangian parameters
– gaugino,scalar masses / mixings / couplings

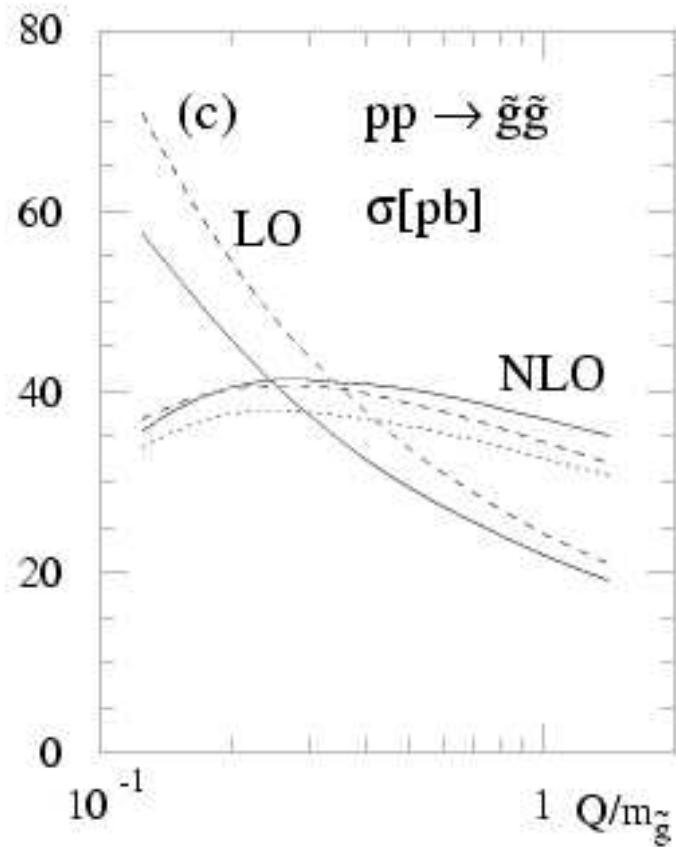
★ RG equations for extrapolation ELW → GUT/PL scale

LHC ANALYSES

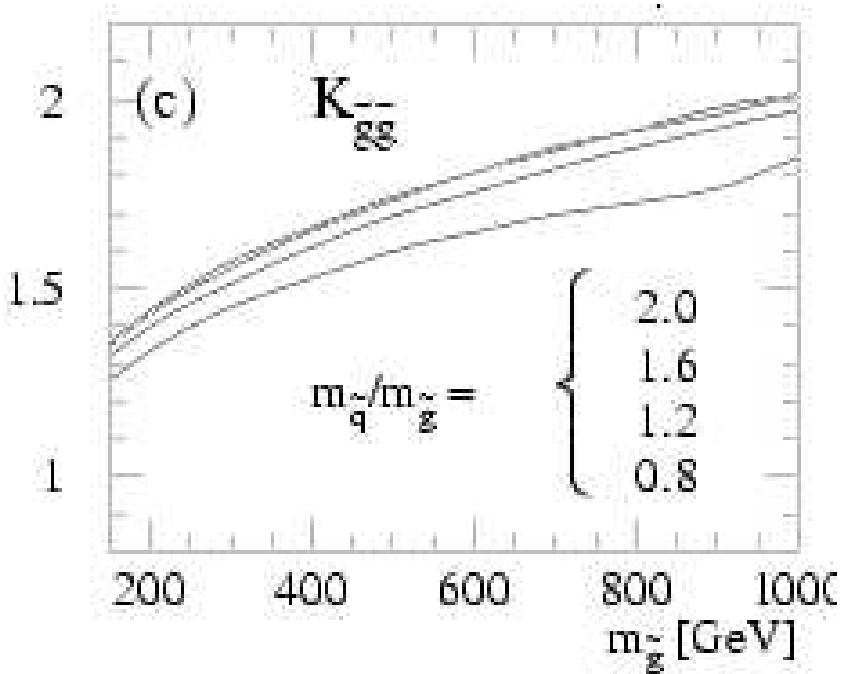
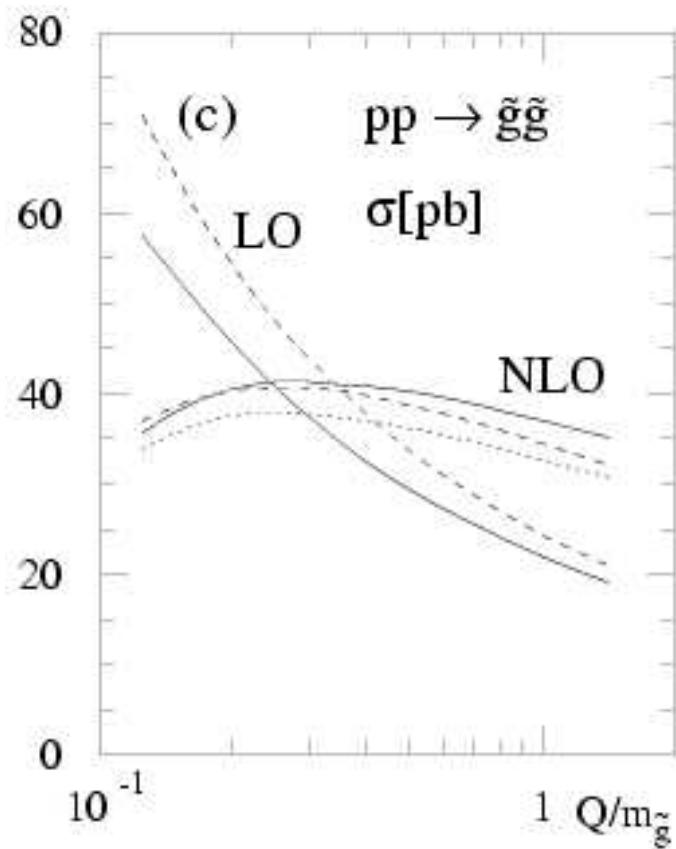
– SPARTICLE DECAYS \tilde{q}, \tilde{g} : under control to 1-loop

Beenakker ea
Guasch ea

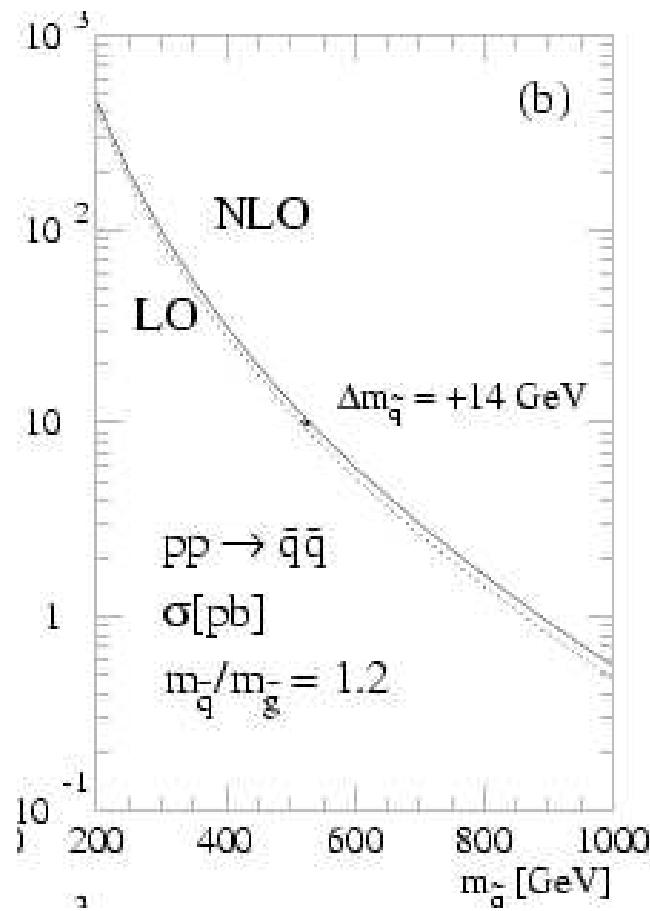
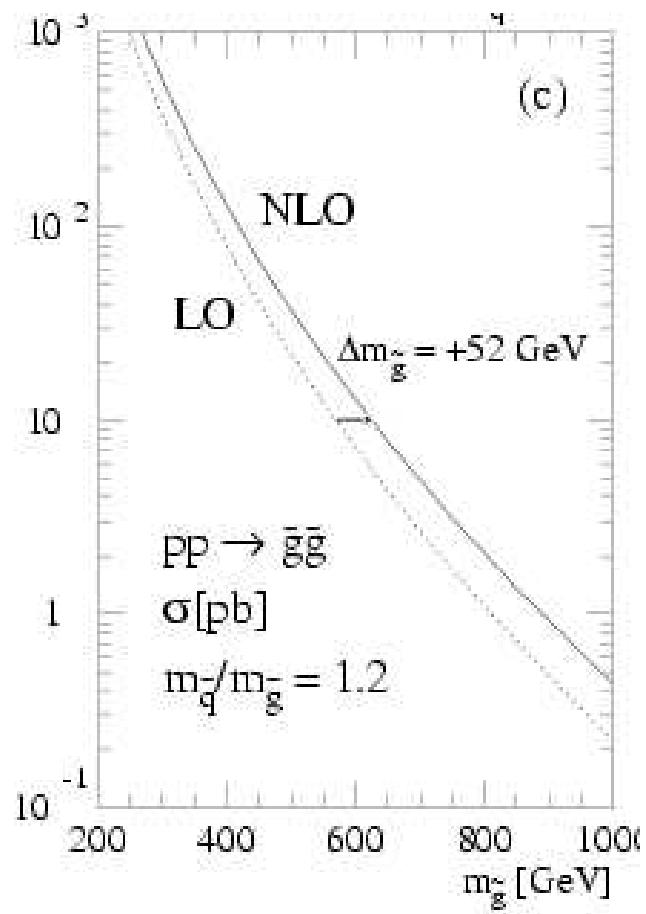
- SQUARK/GLUINO PRODUCTION $PP \rightarrow \tilde{q}/\tilde{g}$: to 1-loop
 Beenakker ea
 Berger ea



- SQUARK/GLUINO/.PRODUCTION $PP \rightarrow \tilde{q}/\tilde{g}$: to 1-loop Beenakker ea
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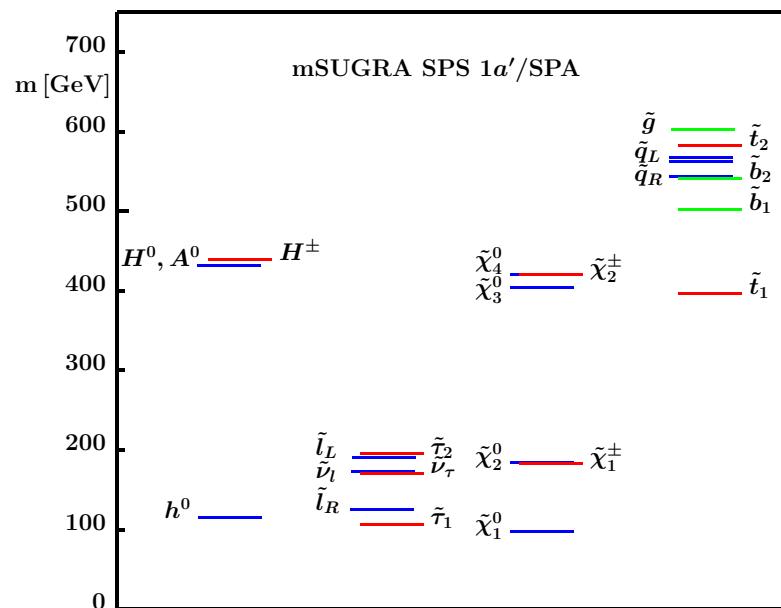
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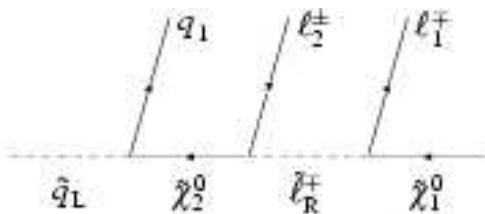
MASSES AT LHC: EDGE EFFECTS

- Spectrum SPS1a/a' :

favorable mass range
for ILC and LHC



- LHC-Chain SPS1a/a' : $\tilde{q} \rightarrow q \tilde{\chi}_2^0 \rightarrow q (\tilde{\ell}\ell) \rightarrow q (\ell\ell) \tilde{\chi}_1^0$



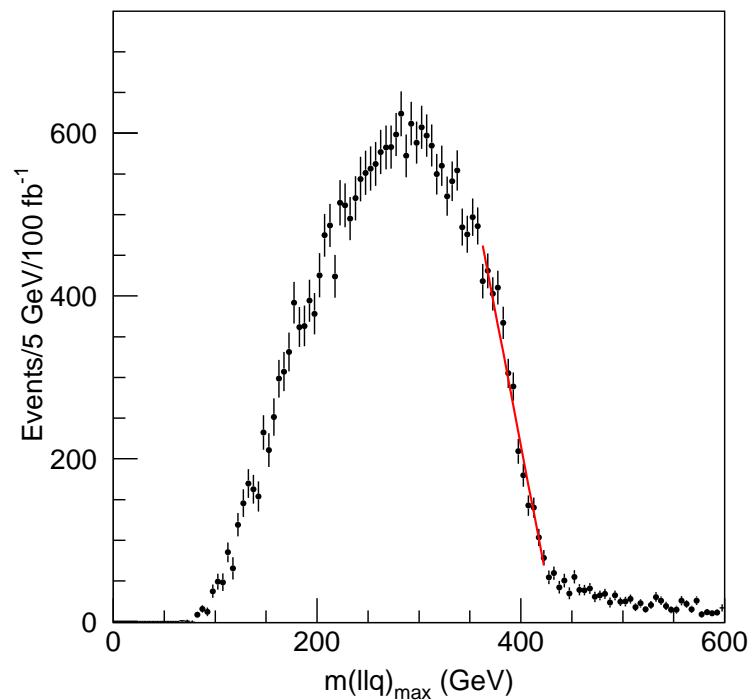
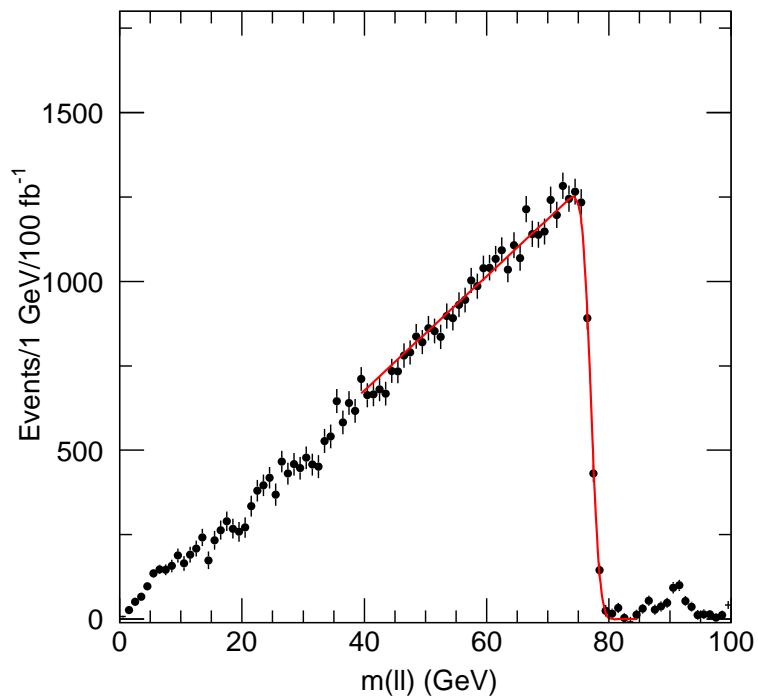
– LHC-Chain SPS1a/a' : $\tilde{q} \rightarrow q \tilde{\chi}_2^0 \rightarrow q (\tilde{\ell}\ell) \rightarrow q (\ell\ell) \tilde{\chi}_1^0$

$$\begin{aligned}
 (m_{\tilde{q}}^2)^{\text{edge}} &= \frac{(m_{\tilde{\chi}_2^0}^2 - m_{l_R}^2)(m_{l_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{l_R}^2} \\
 (m_{\tilde{q}ll}^2)^{\text{edge}} &= \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\chi}_2^0}^2} \\
 (m_{\tilde{q}ll}^2)_{\text{min}} &= \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{l_R}^2)}{m_{\tilde{\chi}_2^0}^2} \\
 (m_{\tilde{q}ll}^2)_{\text{max}} &= \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{l_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{l_R}^2} \\
 (m_{\tilde{q}ll}^2)^{\text{true}} &= [(m_{\tilde{q}_L}^2 + m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{l_R}^2)(m_{l_R}^2 - m_{\tilde{\chi}_1^0}^2) \\
 &\quad - (m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)\sqrt{(m_{\tilde{\chi}_2^0}^2 + m_{l_R}^2)^2(m_{l_R}^2 + m_{\tilde{\chi}_1^0}^2)^2 - 16m_{\tilde{\chi}_2^0}^2m_{l_R}^4m_{\tilde{\chi}_1^0}^2} \\
 &\quad + 2m_{l_R}^2(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)] / (4m_{l_R}^2m_{\tilde{\chi}_2^0}^2)
 \end{aligned}$$

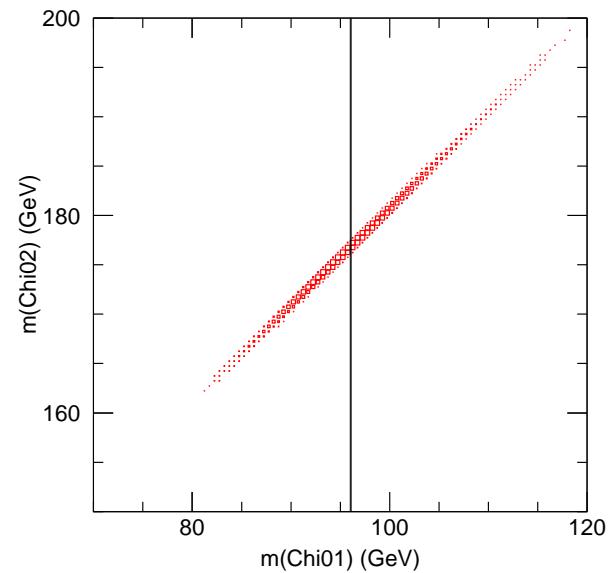
⇒ mass differences with high precision

⇒ absolute values less: escaping light $\tilde{\chi}_1^0$ ⇒

– LHC-Chain SPS1a/a' : $\tilde{q} \rightarrow q \tilde{\chi}_2^0 \rightarrow q (\tilde{\ell}\ell) \rightarrow q (\ell\ell) \tilde{\chi}_1^0$

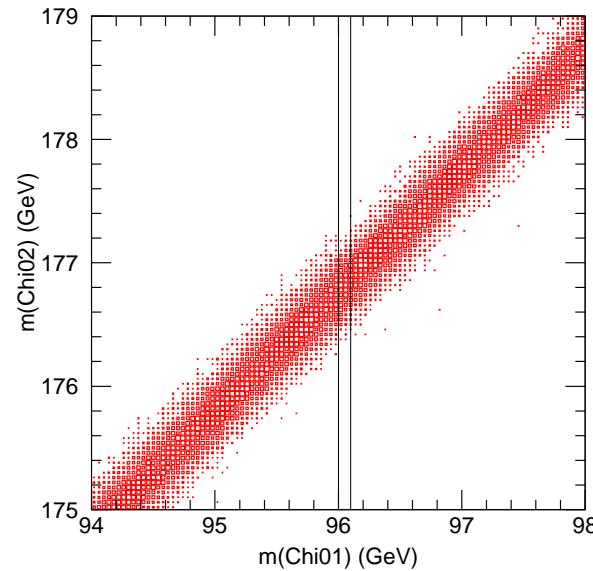
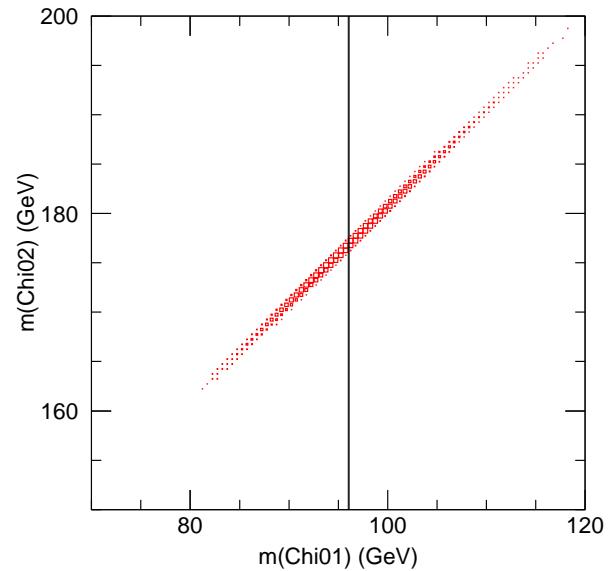


LHC-Chain SPS1a/a' : $\tilde{q} \rightarrow q \tilde{\chi}_2^0 \rightarrow q (\tilde{\ell}\ell) \rightarrow q (\ell\ell) \tilde{\chi}_1^0$



LHC strong correlations with χ_1^0

LHC-Chain SPS1a/a' : $\tilde{q} \rightarrow q \tilde{\chi}_2^0 \rightarrow q(\tilde{\ell}\ell) \rightarrow q(\ell\ell) \tilde{\chi}_1^0$



LHC strong correlations with $\tilde{\chi}_1^0$: resolved by LC

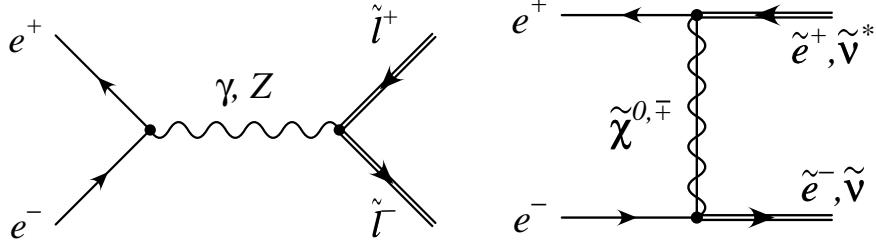
I	Mass, ideal	“LHC”	“LC”	“LHC+LC”
$\tilde{\chi}_1^\pm$	179.7			
$\tilde{\chi}_2^\pm$	382.3	—		
$\tilde{\chi}_1^0$	97.2	4.8		
$\tilde{\chi}_2^0$	180.7	4.7		
$\tilde{\chi}_3^0$	364.7			
$\tilde{\chi}_4^0$	381.9	5.1		
\tilde{e}_R	143.9	4.8		
\tilde{e}_L	207.1	5.0		
$\tilde{\nu}_e$	191.3	—		
$\tilde{\mu}_R$	143.9	4.8		
$\tilde{\mu}_L$	207.1	5.0		
$\tilde{\nu}_\mu$	191.3	—		
$\tilde{\tau}_1$	134.8	5-8		
$\tilde{\tau}_2$	210.7	—		

II	Mass, ideal	“LHC”	“LC”	“LHC+LC”
\tilde{q}_R	547.6	7-12		
\tilde{q}_L	570.6	8.7		
\tilde{t}_1	399.5			
\tilde{t}_2	586.3			
\tilde{b}_1	515.1	7.5		
\tilde{b}_2	547.1	7.9		
\tilde{g}	604.0	8.0		
h^0	110.8	0.25		
H^0	399.8			
A^0	399.4			
H^\pm	407.7	—		

LC ANALYSES

- CHARGINOS, NEUTRALINOS : $e^+e^- \rightarrow \tilde{\chi}\tilde{\chi}$ Öller ea
Fritzsche ea
- SLEPTONS, SNEUTRINOS : $e^\pm e^- \rightarrow \tilde{\ell}\tilde{\ell}$ Freitas ea
Kovarik ea, Arhrib ea

Production :



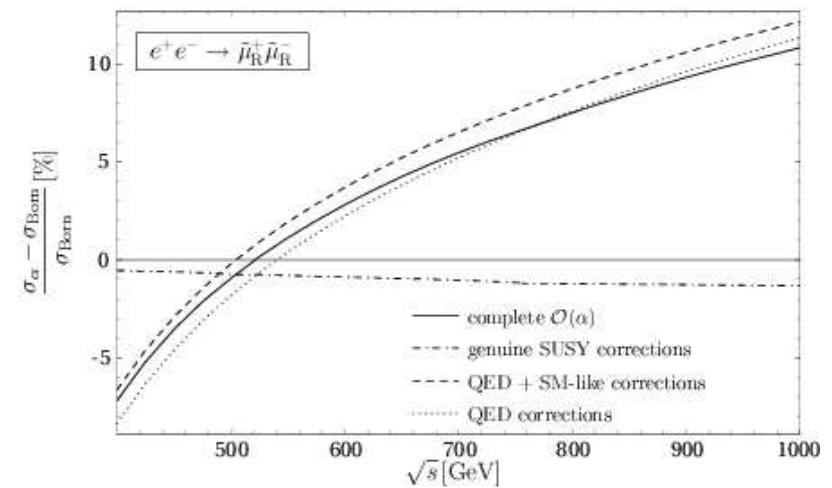
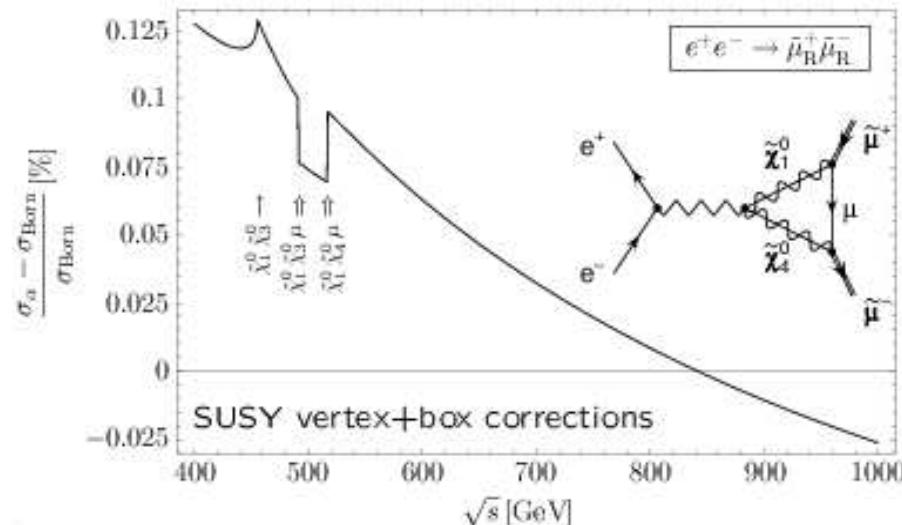
wonderful theoretical laboratory : threshold effects
analyticity of amplitudes

near threshold : Sommerfeld rescattering [Coulomb γ exch $\rightarrow \beta^{-1} \times \beta \sim 1$]

non-zero Breit-Wigner widths \rightarrow gauge invariance restored by adding continuum final states \sim off-shell decays :

$$e^+ e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^- \rightarrow \tilde{\mu}^+ + \mu^- \tilde{\chi}_1^0$$

continuum : one-loop corrections completed
rich particle mass spectrum: anomalous thresholds



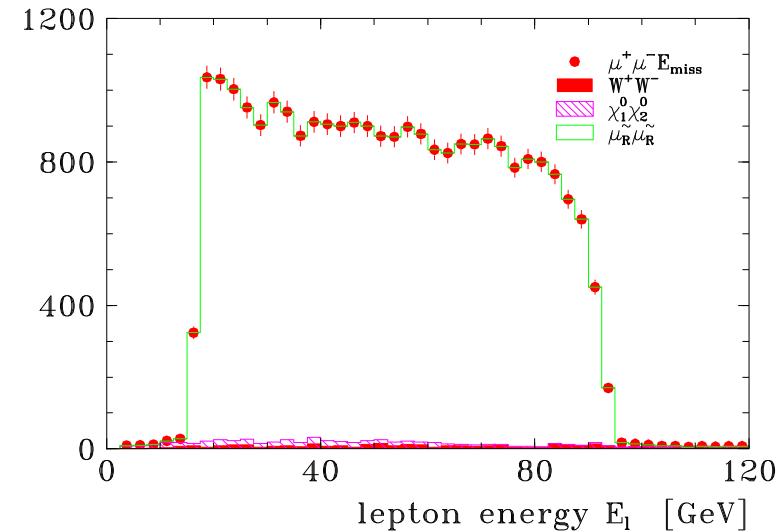
MASSES at LC

a) edge effects: $\tilde{\mu}_R \rightarrow \mu + \tilde{\chi}_1^0$

$$m_{\tilde{\ell}} = \sqrt{s} \sqrt{E_+ E_-} / (E_+ + E_-)$$

$$m_{\tilde{\chi}_1^0} = m_{\tilde{\ell}} \sqrt{1 - 2(E_+ + E_-)/\sqrt{s}}$$

precision on $\tilde{\chi}_1^0$ increased by $\sim 10^2$



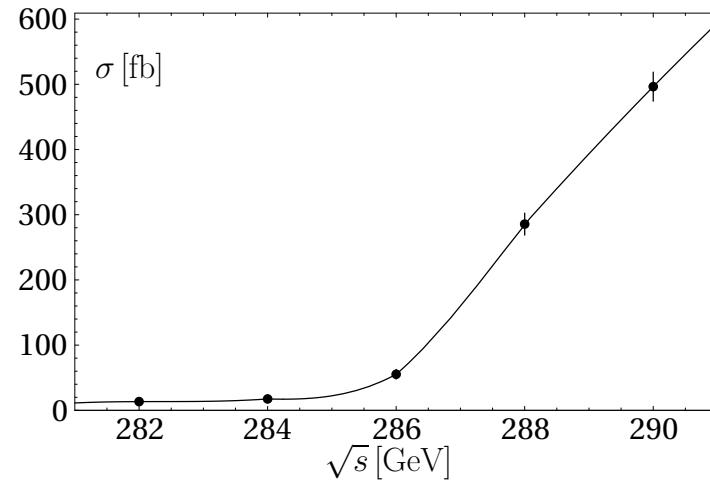
b) threshold excitations:

$$e^+ e^- \rightarrow \tilde{\mu}_R^+ + \tilde{\mu}_R^- \rightarrow \mu^+ \mu^- + E_{miss}$$

P-wave: slow β^3 rise

$$e^- e^- \rightarrow \tilde{e}_R^- + \tilde{e}_R^- \rightarrow e^- e^- + E_{miss}$$

S-wave: fast β rise



SUMMARY: LHC/LC:

LHC, LC

LHC+LC

Coherent LHC+LC
analyses complete
and increase
resolution of SUSY
picture significantly

	Mass, ideal	“LHC”	“LC”	“LHC+LC”
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{\chi}_3^0$	364.7		3-5	3-5
$\tilde{\chi}_4^0$	381.9	5.1	3-5	2.23
\tilde{e}_R	143.9	4.8	0.05	0.05
\tilde{e}_L	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\mu}_L$	207.1	5.0	0.5	0.5
$\tilde{\nu}_\mu$	191.3	–		
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1

SUMMARY: LHC/LC:

LHC, LC

LHC+LC

II	Mass, ideal	“LHC”	“LC”	“LHC+LC”
\tilde{q}_R	547.6	7-12	—	5-11
\tilde{q}_L	570.6	8.7	—	4.9
\tilde{t}_1	399.5		2.0	2.0
\tilde{t}_2	586.3		—	
\tilde{b}_1	515.1	7.5	—	5.7
\tilde{b}_2	547.1	7.9	—	6.2
\tilde{g}	604.0	8.0	—	6.5
h^0	110.8	0.25	0.05	0.05
H^0	399.8		1.5	1.5
A^0	399.4		1.5	1.5
H^\pm	407.7	—	1.5	1.5

input : masses $\tilde{\chi}^{\pm,0}, \tilde{g}, \tilde{\ell}, \tilde{q}, higgs$

pol x-secs $e^+e^- \rightarrow \tilde{\chi}\tilde{\chi}, \tilde{\ell}\tilde{\ell}$

Born analysis: analytical

Choi ea

Boos ea, ...

$$|\mu| = M_W \left[M_\chi^+ + M_\chi^- (\cos 2\phi_R + \cos 2\phi_L) \right]^{1/2}$$

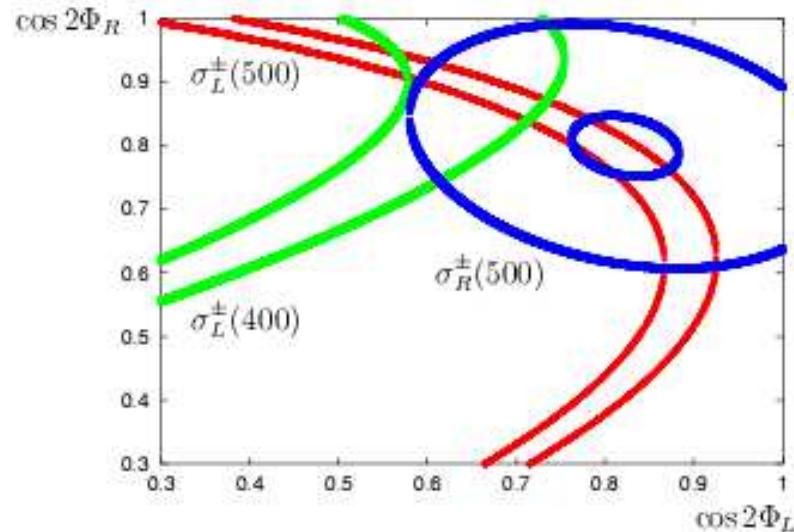
\Rightarrow LHC not sufficient for complete parameter set:
 $[\tilde{\chi}_{1,2,4}^0] : / [M_{1,2}, \mu, \tan \beta]$

$$|M_1| = \left[\sum_i m_{\tilde{\chi}_i^0}^2 - M_2^2 - \mu^2 - 2M_Z^2 \right]^{1/2}$$

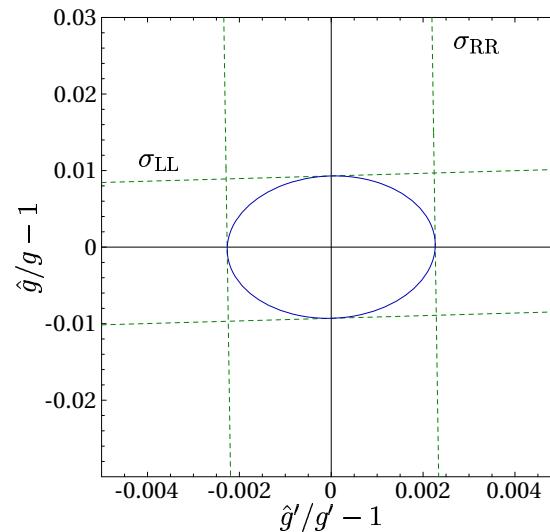
\Rightarrow ILC not sufficient:
 $/ [\tilde{g}] \sim [M_3]$

$$|M_3| = m_{\tilde{g}}$$

MIX IN $\tilde{\chi}^{\pm,0}$ SECTOR * :



YUKAWA = GAUGE IDENTITY:



⇐ Crucial elements of basic Lagrangian at electroweak scale can be reconstructed

* [Choi ea], Desch ea

\oplus loops :

integral LHC/LC analysis : $\mathcal{O} = \mathcal{O}[\mathcal{MSM}]$ Martin, Vaughn, Pierce ea
 \Leftarrow light Higgs h Carena ea, Heinemeyer ea

EXC	LHC	LC	LHC+LC	SPS1a
M_1	102.45 ± 5.3	102.32 ± 0.1	102.23 ± 0.1	102.2
M_2	191.8 ± 7.3	192.52 ± 0.7	191.79 ± 0.2	191.8
M_3	578.67 ± 15	→	588.05 ± 11	589.4
$M_{\tilde{q}1L}$	550.72 ± 13	→	553.32 ± 6.5	553.7
$M_{\tilde{u}R}$	528.91 ± 20	→	531.70 ± 15	532.1
$M_{\tilde{d}R}$	526.2 ± 20	→	528.90 ± 15	529.3
A_t	-507.8 ± 91	-501.95 ± 2.7	-505.24 ± 3.3	-504.9
μ	345.21 ± 7.3	344.34 ± 2.3	344.36 ± 1.0	344.3
$\tan \beta$	10.22 ± 9.1	10.26 ± 0.3	10.06 ± 0.2	10

SFitter: Zerwas,D ea
[Fittino: Bechtle ea]

3. EXTRAPOLATION TO GUT SCALE

high-precision measurements of LE Lagrangian parameters

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- ⇒ extrapolate to high scale:
- symmetries/universal behavior?
 - impact of high-scale physics?

transport: RG Equations [\leftarrow up to 3 loops : Jack ea]

minimal SUGRA

universal GUT scale params
SPS1a/a':

$$\begin{aligned} b \rightarrow s\gamma &= 3.0 \cdot 10^{-4} \\ m_h &= 115.4 \text{ GeV} \\ \Delta a_\mu &= 34 \cdot 10^{-10} \\ \Omega_{cdm} h^2 &= 0.10 \end{aligned}$$

gaugino mass	$M_{1/2}$	250 GeV
scalar mass	M_0	100/70 GeV
trilin cplg	A_0	-100/-300 GeV
signum μ	$sgn[\mu]$	+
higgs mix	$\tan \beta$	10

RGE's:

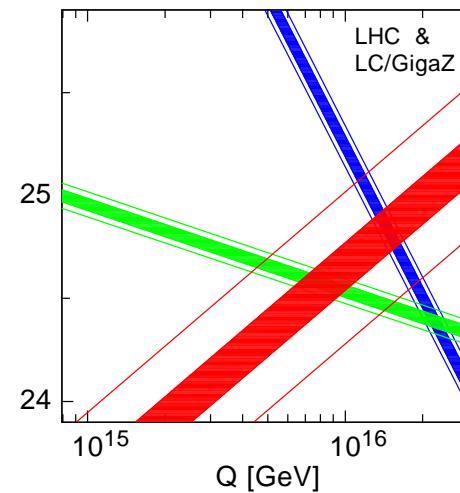
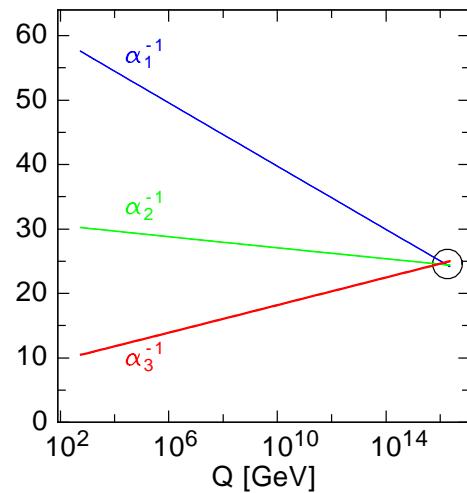
gauge couplings	:	$\alpha_i = Z_i \alpha_U$
gaugino mass parameters	:	$M_i = Z_i M_{1/2}$
scalar mass parameters	:	$M_{\tilde{j}}^2 = M_0^2 + c_j M_{1/2}^2 + \sum_{\beta=1}^2 c'_{j\beta} \Delta M_{\beta}^2$
trilinear couplings	:	$A_k = d_k A_0 + d'_k M_{1/2}$
Z transporters	:	$Z_i^{-1} = 1 + b_i \frac{\alpha_U}{4\pi} \log \left(\frac{M_U}{M_Z} \right)^2$ for $i = \text{U}(1), \text{SU}(2), \text{SU}(3)$

c_j	:	Z_j	couplings, M_i : explicit linear connections
c'_{ij}	:	~ 1	$M_{\tilde{j},H}^2$ implicit connections :
$\Delta M_{\tilde{j}}^2$:	small for gn = 1,2 large for gn = 3 $[Z, M_{1/2}, M_0^2, yuk]$	$M_{\tilde{L}_1}^2 = M_0^2 + 0.5M_{1/2}^2$ $M_{\tilde{Q}_1}^2 = M_0^2 + 5.0M_{1/2}^2$ $M_{H_2}^2 = -0.03M_0^2 - 1.3M_{1/2}^2 + ..$
d_k	:	~ 1 for gn = 1,2 $\sim 10^{-1}$ for gn = 3	$A_t = A_0$ insensitive [fp] Carena ea
d'_k	:	~ 1	

Approaches:

- top-down: theory parametrically defined at high scale
 - evolved down per RG
 - compared directly with data
 - ⇒ quality of fit not reflecting truth of theory
 - bottom-up: exp information exploited to maximum extent possible:
 - maximum information at high scale,
 - solely based on measurements
- ⇒ methods applied both ways to gauge couplings
extended, here, to soft SUSY breaking terms

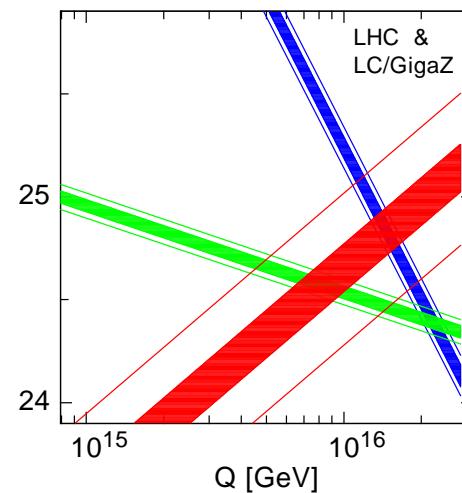
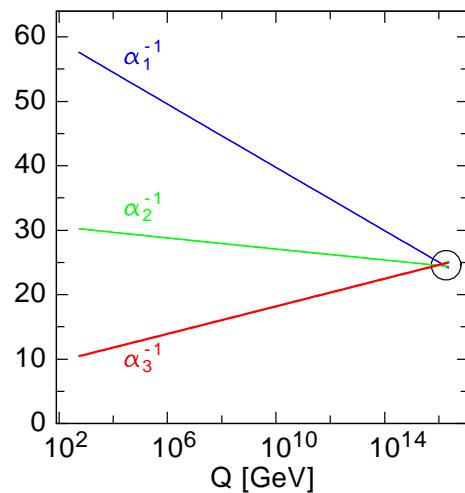
Evolution: 1. present electroweak/strong gauge couplings
 \oplus SUSY threshold corrections \sim LHC
 \Rightarrow grand unification at $\sim 2\sigma$



	Present/"LHC"	GigaZ/"LHC+LC"
M_U	$(2.36 \pm 0.06) \cdot 10^{16}$ GeV	$(2.360 \pm 0.016) \cdot 10^{16}$ GeV
α_U^{-1}	24.19 ± 0.10	24.19 ± 0.05
$\alpha_3^{-1} - \alpha_U^{-1}$	0.97 ± 0.45	0.95 ± 0.12

GAUGE COUPLINGS

Evolution: 1. present electroweak/strong gauge couplings
 \oplus SUSY threshold corrections \sim LHC

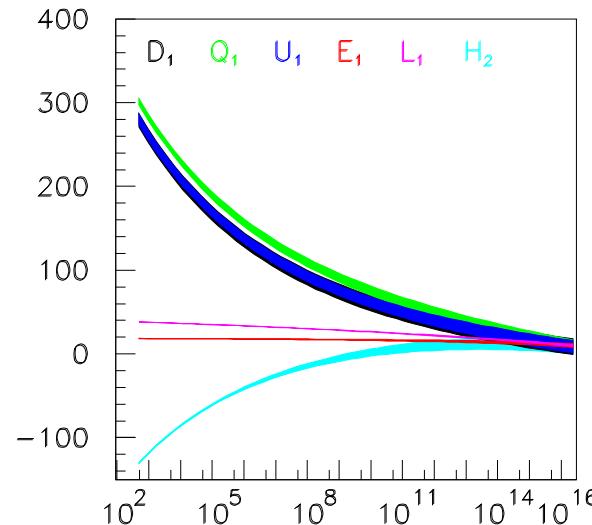
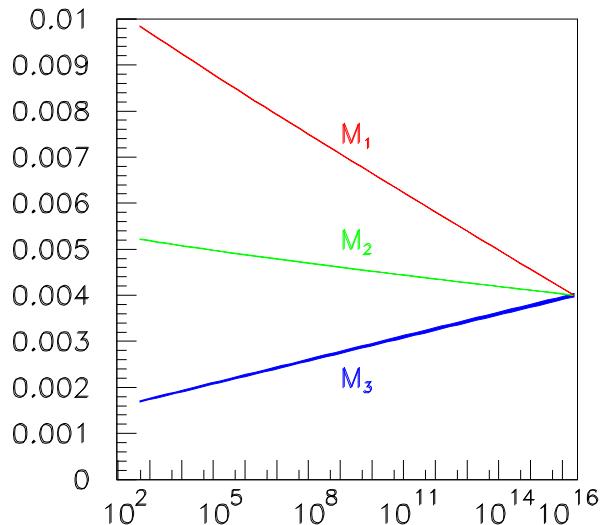


2. GigaZ improvement of gauge couplings $\Delta \sin^2 \theta_W \simeq 10^{-5}$, $\Delta \alpha_s \simeq 10^{-3}$
 \oplus “LHC+LC” completed threshold corrections

$\Rightarrow \alpha_3^{-1} - \alpha_U^{-1}$: can establish GUT-scale physics impact / pres. at 8σ level

UNIVERSALITY OF MASS PARAMETERS

Evolution : Gaugino and scalar mass parameters

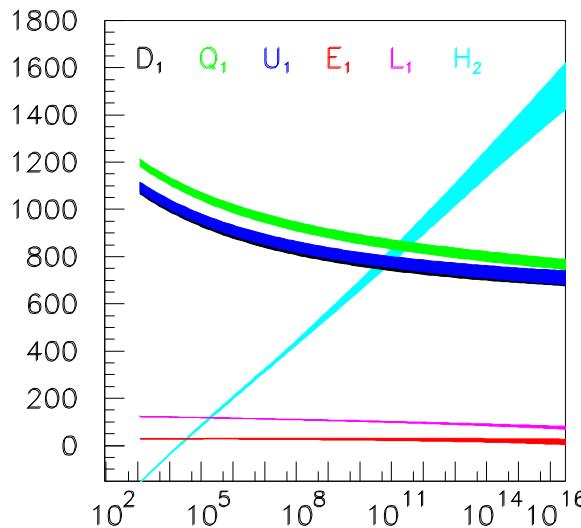
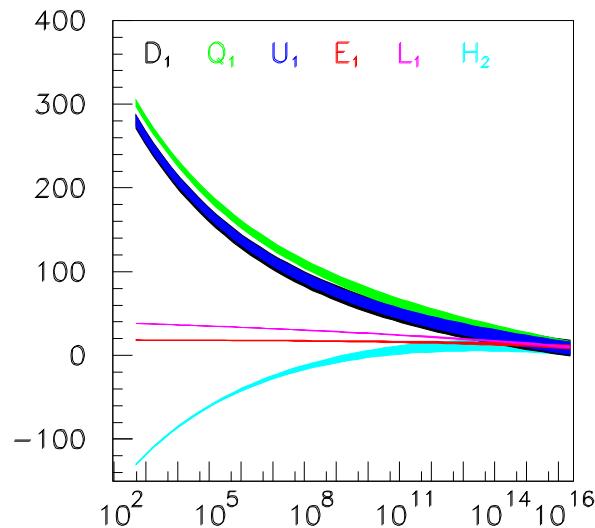


$M_i \rightarrow M_{1/2}$	excellent	$\sim 10^{-3}/10^{-2}$
$M_{\tilde{\ell}}^2 \rightarrow M_0^2$	very good	$a \text{ few } 10^{-2}$
$M_{\tilde{Q}}^2 \rightarrow M_0^2$	abs:good / rel:improve	$a \text{ few } 10^{-1}$

UNIVERSALITY OF MASS PARAMS

Evolution : Scalar mass parameters

mSUGRA vs GMSB



⇒ evolution distinctly different

Bagger ea

general analyses: Kane ea

UNIVERSALITY OF MASS PARAMETERS

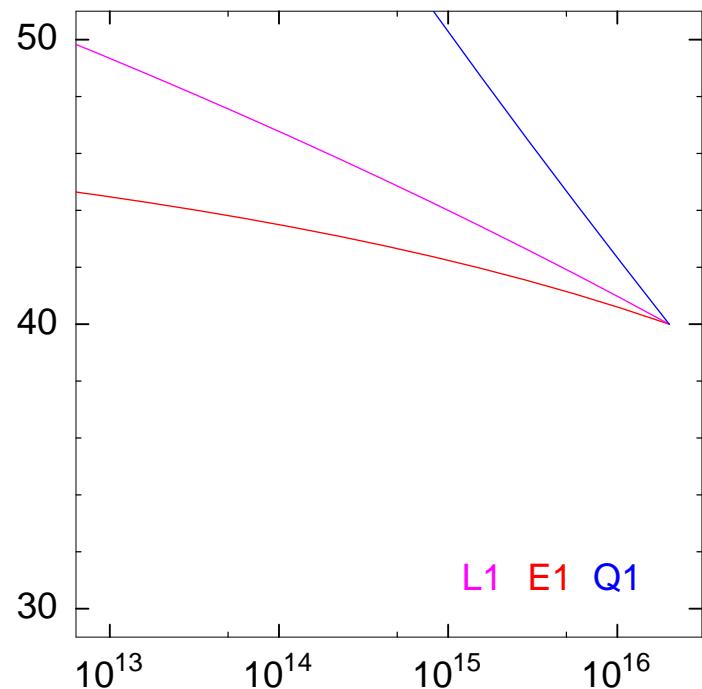
Evolution : Gaugino and scalar mass parameters \Rightarrow top-down evaluation

	Parameter, ideal	Experimental error
M_U	$2.36 \cdot 10^{16}$ GeV	$2.2 \cdot 10^{14}$ GeV
α_U^{-1}	24.19	0.05
$M_{1/2}$	250. GeV	0.2 GeV
M_0	100. GeV	0.2 GeV
A_0	-100. GeV	14 GeV
μ	357.4 GeV	0.4 GeV
$\tan \beta$	10.	0.4

\Rightarrow EXCELLENT PARAMETRIC ANALYSIS

$m_\nu \neq 0$: extending $SU(5) \Rightarrow SO(10) \rightarrow SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$
generating neutrino mass by seesaw mechanisms

intermediate seesaw scale $M[\nu_R]$ directly measurable?

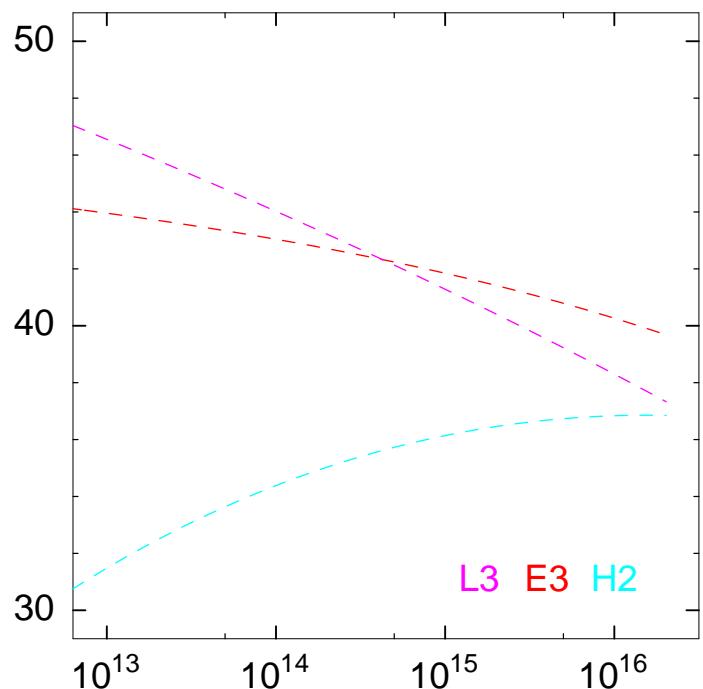


ν_R fields affect running through
Yukawa couplings \Rightarrow
only 3rd generation + Higgs

IF parameters of GUT theory
universal
 \Rightarrow universality in 1st/2nd gene-
ration directly observable

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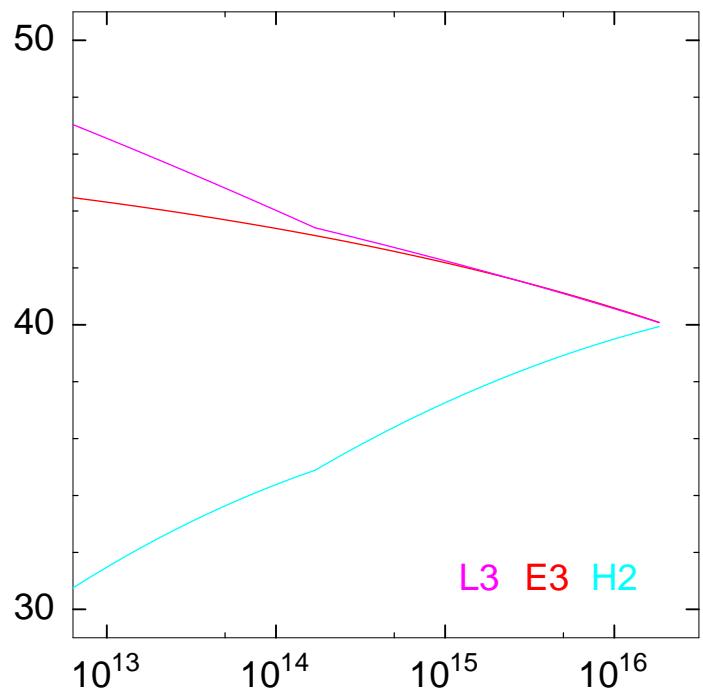


ν_R fields affect running through
Yukawa couplings:
only 3rd generation + Higgs

IF parameters of GUT theory
universal
 \Rightarrow universality in 1st/2nd generation directly observable
 \Rightarrow no universality in 3rd gen / H_2

$m_\nu \neq 0$: extending $SU(5) \Rightarrow SO(10) \rightarrow SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$
generating neutrino mass by seesaw mechanisms

intermediate seesaw scale $M[\nu_R]$ directly measurable?



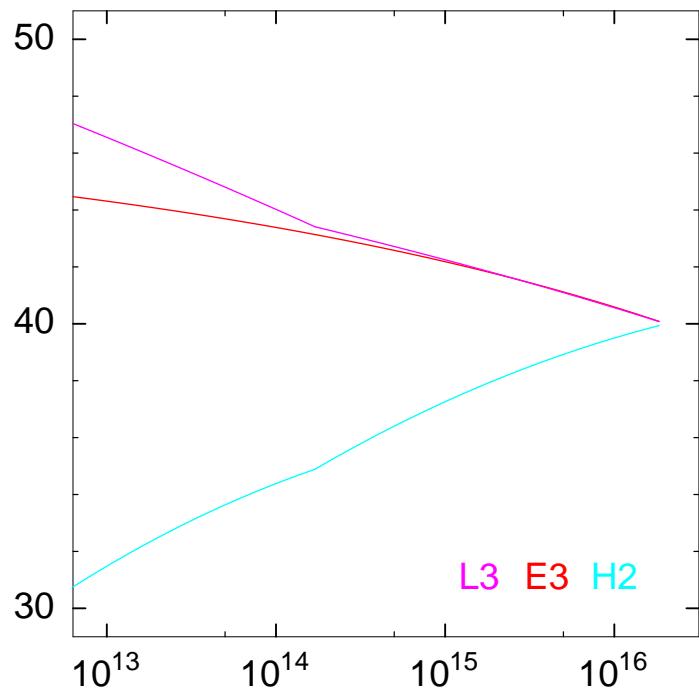
ν_R fields affect running through
Yukawa couplings:
only 3rd generation + Higgs

IF parameters of GUT theory
universal
 \Rightarrow universality in 1st/2nd gene-
ration directly observable
 \Rightarrow in 3rd generation only if kink
due to seesaw ν_R mass built-in

$m_\nu \neq 0$: extending $SU(5) \Rightarrow SO(10) \rightarrow SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$
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qualified “yes”: Baer ea



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STRING EFFECTIVE THEORY

Binetruy ea, Brignole ea,

Kane ea, Love ea,..

scenario : superstring theories with orbifold compactification,
conjectured from non-perturbative mechanisms:

- dilaton field S
- moduli fields T

SUSY breaking induced by non-zero vev's,
associated with Goldstino $\tilde{G} \in [\tilde{S}, \tilde{T}]$:

$\tilde{G} = \sin \theta \tilde{S} + \cos \theta \tilde{T}$: $\sin \theta$ leading \rightarrow dilaton-type/universal
 $\cos \theta$ leading \rightarrow moduli-type/non-universal

gaugino masses : $M_i = \frac{\alpha_i}{4\pi} m_{3/2} \langle S \rangle \sqrt{3} \sin \theta + \mathcal{HO}\{\langle T \rangle, \delta_{GS}, \dots\}$

scalar masses : $M_j^2 = m_{3/2}^2 [1 + n_j \cos^2 \theta] + \mathcal{HO}\{\langle T \rangle, \dots\}$

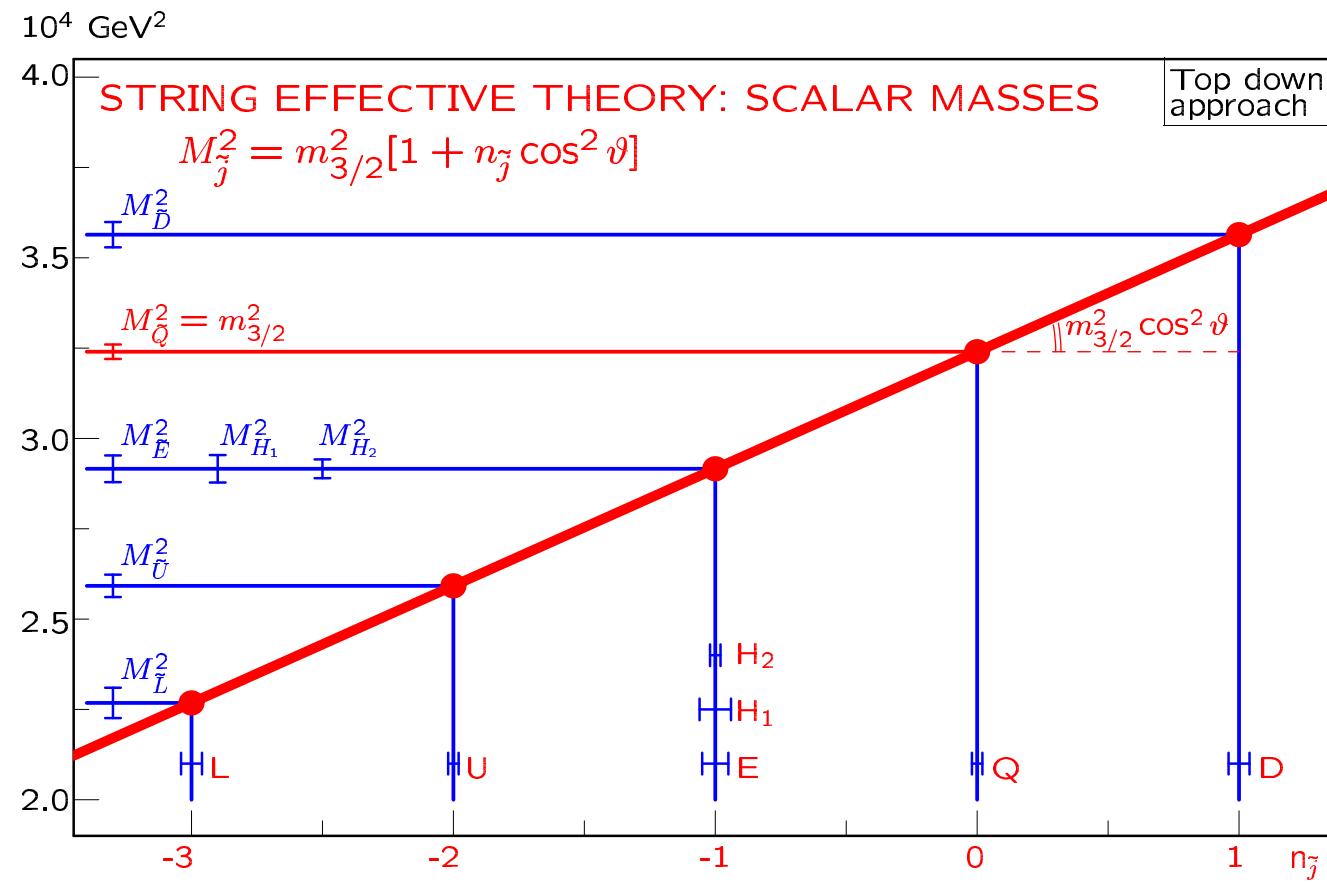
↑ integer modular weights

Parameter analysis :

Parameter	Ideal	Reconstructed		
$m_{3/2}$	180	179.9	\pm	0.4
$\langle S \rangle$	2	1.998	\pm	0.006
$\langle T \rangle$	14	14.6	\pm	0.2
$\sin^2 \theta$	0.9	0.899	\pm	0.002
g_s^2	0.5	0.501	\pm	0.002
δ_{GS}	0	0.1	\pm	0.4
n_L	-3	-2.94	\pm	0.04
n_E	-1	-1.00	\pm	0.05
n_Q	0	0.02	\pm	0.02
n_U	-2	-2.01	\pm	0.02
n_D	+1	0.80	\pm	0.04
n_{H_1}	-1	-0.96	\pm	0.06
n_{H_2}	-1	-1.00	\pm	0.02

precision at per-cent level for integer modular weights testing stringently
 string-theoretical approach

Parameter analysis : “SUSY Chew-Frautschi Plot”



4. SUMMARY

1. Coherent “LHC+LC” analyses establish SUSY scenario at electroweak scale comprehensively and with high precision:
non-colored \Leftarrow per-mille level
colored \Leftarrow per-cent level
2. Fundamental SUSY theory at GUT/Planck scale can be reconstructed / intermediate scales detected: universal mSUGRA, LR-extended, ...
3. String-effective parameters can be measured through gauge couplings and gaugino/scalar SUSY breaking parameters

[P decay / ν physics / cosmology]
high-precision high-energy experiments \Rightarrow

LHC+ILC may be interpreted as “Telescope to Planck-scale physics”
– if supersymmetry is realized in Nature and mass range favorable

Material

W.Beenakker, R.Höpker, M.Spira, and P.M.Zerwas	squarks, gluinos	NP B492 (1997) 51 hep-ph/9610490
A.Freitas, A. v.Manteuffel, P.M.Zerwas	sleptons	EPJ C34 (2003) 487 hep-ph/0310182/0408341
G.Polesello ea	LHC error analysis	LHC/LC in Phys.Rep.C
U.Martyn	ILC error analysis	<i>ditto</i>
R.Lafaye, T.Plehn, D.Zerwas	Sfitter NLO analysis	<i>ditto</i> hep-ph/0404282
S.Y.Choi ea	gauginos/higgsinos	EPJ C22 (2001) 563 hep-ph/0108117
G.A.Blair, W.Prod, P.M.Zerwas	high-scale extrapol.	PR D63 (2001) 017703 EPJ C27 (2003) 263 hep-ph/0210058
B.Allanach ea	LHC+LC analysis	LHC/LC in Phys.Rep.C hep-ph/0403133